High-Resolution Far-Infrared Spectroscopy on SOFIA
A White Paper for NASA's Space Science Roadmap Revision
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SOFIA, the Stratospheric Observatory for Infrared Astronomy, is now in development, and is expected to begin astronomical observations early in 2005. SOFIA was justified in large degree to enable high-resolution spectroscopy throughout the far-infrared (FIR) wavelength region, a unique capability among planned astrophysics missions. This white paper summarizes the rationale for a generic SOFIA Facility Spectrometer - SFS - following the guidelines suggested by the Structure and Evolution of the Universe Subcommittee (SEUS) for requested revisions to the NASA Space Science Roadmap. The questions are those of the SEUS; the paper is submitted both to the SEUS and to the Origins Subcommittee.

1. "What are the principal science goals of this mission, and what new areas of discovery space does it open?"

The interstellar medium (ISM) plays a central role in the evolution of our own and other galaxies. The ISM is the repository of stellar ashes, injected either by gentle winds or cataclysmic explosions. The effluent gas and condensing dust eventually become raw materials from which new stars and planetary systems form. Enrichment with synthesized elements accompanies the stellar life cycle, driving galactic evolution.

Molecular, neutral atomic, and ionized gas in the ISM is characterized by numerous spectral features at infrared and submillimeter wavelengths which enable astrophysics not possible in other bands. Most of these wavelengths are blocked by the earth's atmosphere from ground-based sites, but most are accessible from SOFIA, as indicated in Figure 1. An SFS is needed to exploit this potential, to explore the relationship between stars and the ISM in detail.

The power of spectroscopy across these wavelengths was demonstrated from the KAO and extended in the infrared from ISO. Nearly a hundred spectral features of atoms, ions, and molecules were observed from the KAO, and vastly more from ISO, many never previously observed even in laboratories. The larger SOFIA telescope and modern instrumentation assure that an SFS would enhance and elaborate on these discoveries and those obtained in imaging and complementary spectroscopy from ISO, SIRTF, SOFIA, Herschel and Astro-F. The variety of topics awaiting exploration in a new domain of higher spatial and spectral resolution include massive and low-mass star formation, recycling in supernova remnants and planetary nebulae, interstellar and circumstellar chemistry, physics of shocks, elemental abundances in obscured regions, AGN versus starburst activity, and the Galactic Center. Discovery potential for the SFS exists in all these areas.

A host of critically important diagnostic transitions lie in the FIR spectral region, including [C II] at 158 μm, the principal coolant of the ISM and a good distance indicator, and [O I] at 63 μm, the primary tracer of warm, dense atomic gas. Many of the valuable spectral signatures are widely separated in wavelength, but their measurement is a prerequisite for a full understanding of source physics. Lines of [S I] 25 μm, [Fe II] 26 μm, [Si II] 35 μm and [O I] 63 μm are key diagnostics of shocked gas. Line pairs of [S III] (19 and 33 μm), [O III] (52 and 88 μm), and [N II] (122 and 205 μm) measure densities and allow excitation estimates over a significant range in ionized regions. The [Ne V] (24 μm) and [O IV] (26 μm) lines characterize high excitation regions such as AGN. Lines with similar ionization potential, e.g., [N III] (57 μm) and [O III] (52 μm), provide relative abundance estimates. The goal of an SFS would be to enable as much of this science as practical in a single instrument, recognizing that no one instrument can do everything.

To achieve this goal, a strawman SFS should (a) permit contiguous coverage of a wide wavelength range while spectrally imaging close to the SOFIA diffraction limit, (b) provide spectral resolution adequate to detect motions (< 30 km/s) in a variety of sources, and (c) attain sensitivity limited by background photon fluctuations from the sky and telescope. Desirable wavelength coverage would include at least the 25 μm [S I] line and the 158 μm [C II] line, and would preferably extend from the opaque atmospheric absorption just short of the 17 μm J=3->1 H_2 line to the 205 μm [N II] line. Coverage from 17-210 μm was demonstrated with a lower resolution spectrometer on the KAO. The higher resolution (<0.3 km/s) of a coherent (heterodyne) spectrometer is certainly desirable for a number of problems, but suitable technology is currently not available for this entire wavelength range, even for single receivers, whereas direct detection arrays have been demonstrated.

As a facility instrument, an SFS should permit rapid wavelength changes and convenient data handling, enabling comprehensive investigations on a single flight. The full cost for such an instrument may be ~$15 M, depending on the availability of previously developed technology. The cost will be higher than that of a comparable ground-based instrument largely due to airworthiness and packaging requirements. Of course, costs should be minimized by all reasonable means, such as incremental implementation of the detector capability. A major benefit afforded by the SOFIA *modus operandi* is the ability for instruments to incorporate new detector technology as it becomes available. Finally, an SFS would efficiently support a large general investigator community, both from the U.S. and abroad.

Figure 2 shows the resolving power versus wavelength for all planned infrared spectrometers on SOFIA, Herschel, SIRTF, NGST, and Astro-F. Three heterodyne spectrometers populate the upper right hand corner of the plot. In the important spectral region from 17 to 210 μm the line labeled SFS shows the performance achievable with a large echelle grating spectrometer. This has the spectral resolution and wavelength coverage needed to measure a variety of widely spaced lines as described above. The SFS depicted clearly fills an important gap in the wavelength/resolution space of all planned spectrometers -- both those on other facilities and the PI-class instruments on SOFIA. In addition, of course, spectra from the SFS would scientifically complement the full range of capabilities of the missions listed. SIRTF, for example, although having lower angular resolution than SOFIA, will do extensive high-sensitivity imaging and low-resolution spectroscopy shortward of 37 μm , and will spend much of its time doing surveys.

2. "How does the mission bear on science priorities as expressed in the various National Academy survey reports?"

The McKee-Taylor report refers to SOFIA as one of NASA's programs from the decade of the '90s that should be completed; the science rationale is contained in the previous (Bahcall) survey report. Quotes from this document describe how an instrument such as an SFS is central to the recognized science priorities: Page 23: "SOFIA provides the highest-resolution spectroscopy of any planned facility for wavelengths between 30 and 300 μm, and its large aperture will yield high spatial-resolution observations that will complement SIRTF's capabilities." Page 78: "In particular, spectral observations at these wavelengths hold the key to understanding the physics in regions of high-density and moderate temperature that characterize the primitive nebulae around newly formed stars, and the cores of infrared-luminous galaxies and quasars. SOFIA's capabilities for diffraction-limited imaging and high-resolution spectroscopy at wavelengths inaccessible from the ground will complement SIRTF's great sensitivity at infrared and submillimeter wavelengths." Page 79: "Most Important Attributes [of SOFIA]: High-resolution spectroscopy at $\lambda > 30$ μm, 2.5(λ/30 μm) arcsec imaging at $\lambda > 30$ μm, Training of instrumentalists."

Additionally, AIRES (the cancelled SOFIA facility spectrometer) was ranked first in the peer review of 19 instruments proposed. A recent SOFIA-sponsored review committee concluded "We believe a far-infrared spectrometer covering at least the spectral range 30-100 μm at high-resolution is a *sine qua non* for SOFIA."

3. "How does the proposed mission or its technology address national priorities other than curiosity driven-research?"

Cryogenic CMOS integrated circuits developed for FIR photoconductor detectors may be applicable to other cryogenic systems, for example in sensor circuitry for liquid cryogen rocket motors. Optical analysis and manufacturing techniques developed for FIR astronomical instrumentation may likewise find other uses. The development of the SFS would represent an excellent opportunity to involve graduate students and young researchers in the development of state-of-the-art infrared instrumentation. In addition, as a facility instrument, an SFS would play a major role throughout its lifetime in the extensive education program planned for SOFIA.

4. "How does the mission build upon accomplishments of other NASA space science missions, and fit into the strategic plan under which OSS now operates? Is this mission in part a technological precursor to more advanced missions? If so, what are they and what are their goals?"

An SFS would extend the technologies and accomplishments of the Kuiper Airborne Observatory (KAO), the Infrared Astronomical Satellite (IRAS), the Cosmic Background Explorer (COBE), and the Submillimeter Wave Astronomy Satellite (SWAS). It represents an important capability to achieve the goals of the current OSS strategic plan: In the 1997 National Research Council report "A New Strategy for Space Astronomy and Astrophysics" the authors assume the SOFIA development will be completed, and list among their eight highest priority scientific objectives the following two: "Study of star formation by, for example, high-resolution far-infrared and submillimeter observations of protostars, protoplanetary disks, and outflows; Study of the origin and evolution of the elements".

No missions currently in NASA's strategic plan provide the SFS capability. Such an instrument would certainly be considered a precursor for any future mission intended to succeed SOFIA, such as the SAFIR (Single Aperture FIR observatory) mission currently under discussion. The NSF/ESO Atacama Large Millimeter Array (ALMA) is scheduled to start operation with a partial array in 2005 and be completed in 2009; it will address some of the same problems as the SFS, but again with complementary observations. For example, SFS will measure the 84, 119, and 163 μm OH doublets produced in accretion shocks on YSO disks to deduce mass infall rates, whereas ALMA will image the cooler components of the disks to determine their structure.

5. "How do the timescale and goals of this mission compare with those of non-NASA missions? Are there likely to be strategic advantages in international collaboration?"

With current funding limitations, the SOFIA program could likely begin an SFS development in 2006 at the earliest, leading to first light around 2011 or later. ESA's 3.5-m FIR/submillimeter telescope, Herschel, is planned for launch in 2007, has an expected lifetime of at least 3 years, and will study many of the same problems as would users of an SFS. The 70 cm Japanese Astro-F, an infrared survey mission, is scheduled for launch in mid 2003.

Figure 2 shows the spectral resolution as a function of wavelength for the spectrometers planned on the different missions, and clearly exhibits the FIR gap that an SFS would fill. Because of its higher spectral resolution, an SFS would scientifically complement these missions, but they (as well as NASA's SIRTF) will be over considerably before an SFS is commissioned on SOFIA according to present schedules. Nevertheless, an SFS will be capable of observations not permitted by any of these facilities.

International collaboration on an SFS could cut partners' costs, possibly speed development, and provide resilience to eventual budget pressures.

6. "What precursor R&D activity is required to ensure the success of the mission? In what areas of advanced technology would investments most strongly impact cost and performance? In what research areas would investments most strongly impact data analysis and interpretation?"

The technology for an imaging SFS covering the ~20-200 μm range with spectral resolution ≤ 30 km/s is currently in hand. Improvements in FIR detector technology would be most effective in reducing cost and enhancing performance, for example improved quantum efficiency and larger array formats. Of course the SFS should be built with the capability for incorporating advances in detector technology as they become available. Extending coherent receiver performance to operate over this full spectral range with reasonable array formats is also highly desirable, but represents a significant extension of current technology. Further theoretical modeling would assist in identifying key observations and interpreting them.

7. "What kind of partnerships are envisioned for this mission (e.g., academic, international, other US government agency, industrial)?"

Partnerships for building the SFS could involve any combination of academic, government, industrial, and international entities. Certainly scientists around the world are interested in the science the SFS would do and the technology it would incorporate.

Conclusion:

Much of SOFIA's justification was based on science enabled by high-resolution, far-infrared, imaging spectroscopy. If developing the SFS is long delayed, so also will be much of the promise of this unique observatory. We urge endorsement of a far-infrared facility spectrometer development for SOFIA, to begin as soon as possible.

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Fig 1 **Atmospheric Transmission versus Wavelength**

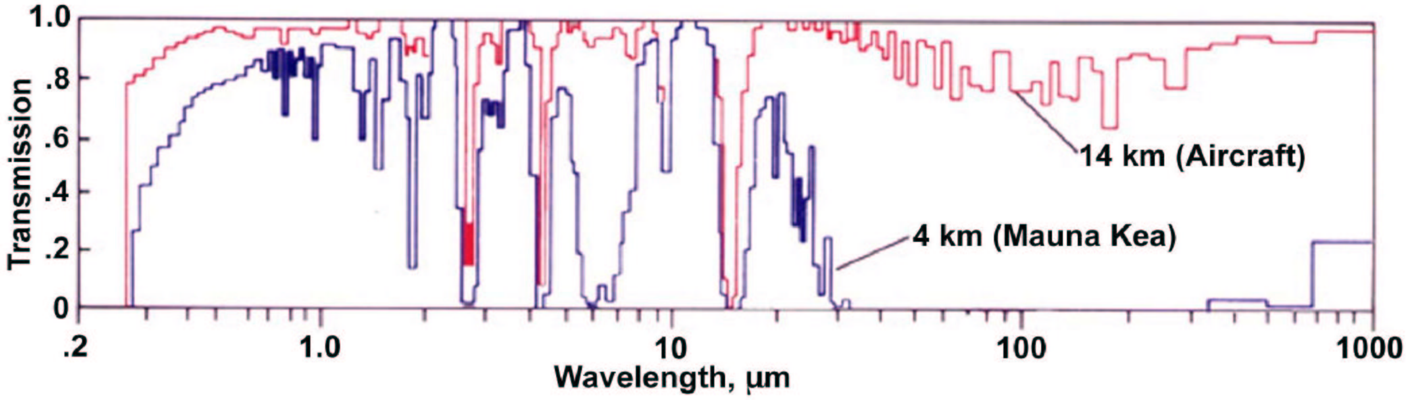

Fig 2 **Anticipated Spectroscopic Capabilities**